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The Square Kilometre Array: A new probe of cosmic magnetism

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Abstract. Magnetic fields are a fundamental part of many astrophysical phenomena, but the evolution, structure and origin of magnetic fields are still unresolved problems in physics and astrophysics. When and how were the first fields generated? Are present-day magnetic fields the result of standard dynamo action, or do they represent rapid or recent field amplification through other processes? What role do magnetic fields play in turbulence, cosmic ray acceleration and structure formation? I explain how the Square Kilometre Array (SKA), a next-generation radio telescope, can deliver stunning new data-sets that will address these currently unanswered issues. The foundation for these experiments will be an all-sky survey of rotation measures, in which Faraday rotation toward $> 10^7$ background sources will provide a dense grid for probing magnetism in the Milky Way, nearby galaxies, and in distant galaxies, clusters and protogalaxies. Using these data, we can map out the evolution of magnetized structures from redshifts $z > 3$ to the present, can distinguish between different origins for seed magnetic fields in galaxies, and can develop a detailed model of the magnetic field geometry of the intergalactic medium and of the overall Universe. In addition, the SKA will certainly discover new magnetic phenomena beyond what we can currently predict or imagine.

Key words: cosmology: large-scale structure – Galaxy: structure – intergalactic medium – magnetic fields – instrumentation: interferometers – techniques: polarimetric

1. Introduction

The Square Kilometre Array[1] (SKA) is a next generation radio telescope, which will have a collecting area of $\sim 10^6$ m^2. With these capabilities, the SKA will be able to answer fundamental questions about the origin and evolution of the Universe.

The international SKA consortium, comprised of representatives from 16 member countries, is currently considering site proposals from Argentina/Brazil, Australia, China, and South Africa. A shortlist will be selected from these site proposals in the second half of 2006.

The specifications for the SKA (Jones 2004) require an angular resolution of $0\farcs02$ at 1.4 GHz, a frequency capability of 0.1–25 GHz, and a field of view of at least 1 deg^2 at 1.4 GHz. While the detailed design for the SKA is yet to be finalised, the SKA Reference Design (Schilizzi 2006) currently consists of a central 5-km core of both steerable dishes and passive aperture tiles, with 50% of the total collecting area distributed on longer baselines, extending out to > 3000 km. The dishes will be outfitted with phased arrays at low frequencies and wide-band feeds at higher frequencies. The aperture array will have a very wide field of view at low frequencies (~ 50 deg^2 at 700 MHz), to allow rapid surveys of redshifted H I. Operations for the SKA are expected to begin in 2015–2020, with a total cost for the instrument of approximately €1.5 billion. An illustration of the layout of the Reference Design is shown in Figure 1.

Five key science projects have been adopted by the SKA International Steering Committee:

- The Cradle of Life (Lazio, Tarter & Wilner 2004);
- Strong Field Tests of Gravity Using Pulsars and Black Holes (Kramer et al. 2004);
- Probing the Dark Ages (Carilli et al. 2004a);
- Galaxy Evolution, Cosmology and Dark Energy (Rawlings et al. 2004);
- The Origin and Evolution of Cosmic Magnetism (Gaensler, Beck & Feretti 2004).

In addition, the theme of "Exploration of the Unknown" (Wilkinson et al. 2004), which emphasises radio astronomy's

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[1] See http://www.skatelescope.org for more information.

Fig. 1. An artist's impression of the SKA Reference Design, showing the central core of dishes and tiles, surrounded by five spiral arms containing stations of dishes. Image created by XILOSTUDIOS for the International SKA Project Office.

outstanding track record of serendipitous discovery, has been adopted as an underlying philosophy for design and costing.

2. Fundamental physical questions

One of the criteria for the key science projects listed above is that they must address important but currently unanswered questions in fundamental physics or astrophysics. For the "Cosmic Magnetism" project, indeed many such questions arise. We can broadly group these questions into three themes, relating to the structure, evolution and origin of magnetic fields.

The most direct goal is to understand the structure of celestial magnetism on all scales, by mapping the geometry and strength of magnetism in the interstellar medium (ISM), intercluster medium (ICM) and intergalactic medium (IGM), all of which are currently poorly characterised, or in the case of the IGM, still yet to be definitively detected. Coupled to these measurements, we lack an understanding of the way in which magnetic fields connect large-scale, ordered flows to small-scale, turbulent flows. Measurements of magnetic fields on all scales are essential to addressing this issue.

Once the field structure has been determined, we can then ask how these magnetic fields evolve. Specifically, we would like to understand the details of how magnetic fields are generated and then maintained over cosmic epochs, in both individual galaxies and in galaxy clusters. We also need to understand the feedback between galaxy evolution and the associated magnetic fields.

Finally, there are the difficult but key questions relating to the origin of magnetic fields. As discussed extensively at this meeting, we have yet to establish if seed fields for galaxies and clusters were primordial, or if they were injected at early epochs by stars, supernovae and AGN. Did magnetic fields trace, or even regulate, structure formation in the early Universe? And ultimately, how and when were the first magnetic fields generated? Major advances on all these questions can be achieved with the SKA.

3. Faraday rotation with the SKA

Faraday rotation will be a crucial component of SKA studies of the magnetic Universe. Not only will the SKA's large collecting area allow the detection of Faraday rotation toward much fainter sources than is possible now, but the high signal-to-noise ratio and large continuum bandwidth will yield accurate rotation measures (RMs) and Faraday-corrected polarisation position angles from a single observation. This is in contrast to current observations, where such measurements often require multiple observations at widely separated frequencies. This approach is not only time-consuming, but may be misleading due to the strong frequency dependence of internal Faraday effects.

For example, in a one hour observation of a 0.1 mJy source with a fractional linear polarisation of 1%, the SKA will make a 10-σ detection of linear polarisation, resulting in an RM error of just 5 rad m^{-2} and an error in intrinsic polarisation position angle of only 10°. Spectacular images of rotation measure and intrinsic polarisation vectors in supernova

remnants, galaxies and clusters can result, all contemporaneous with standard continuum observations.

4. The polarised sky with the SKA

The polarisation of diffuse emission can be difficult to interpret, due to complicated resolution- and frequency-dependent Faraday effects (e.g., Sokoloff et al. 1998). Thus the simplest measurements to make are those toward compact sources which, provided that intrinsic Faraday rotation is minimal, provide a simple measure of the foreground RM along the line-of-sight.

Currently approximately 2000 compact extragalactic sources and 550 pulsars have measured RMs (Xu et al. 2006; Han et al. 2006, and references therein). Over the last several decades, these data have proved to be very powerful probes of magnetic fields in sources ranging from distant Ly-α absorbers to the solar wind. However, as mentioned above, many of these measurements entailed polarisation measurements at widely separated frequencies, resulting both in slow progress and in the possibility of erroneously calculated RMs. Furthermore, the sampling of these RM data is quite sparse — over most of the sky the density of extragalactic RMs is ~ 0.05 deg^{-2}. The situation is somewhat better in the Galactic plane, where recent surveys have identified many hundreds of extragalactic and pulsar RMs (Brown, Taylor & Jackel 2003; Han et al. 2006), bringing the density of measurements at low latitudes up to about ~ 2 deg^{-2}.

To predict the improvements on these data that the SKA can provide, we need to extrapolate. Beck & Gaensler (2004) have convolved an estimate of the probability distribution of fractional polarisation for extragalactic sources with standard $\log N - \log S$ differential source count models to derive a distribution of "$\log N - \log P$", predicting the density of polarised sources and RM measurements on the sky.

An example of what these calculations predict is shown in Figure 2, where we illustrate what a five minute integration with the SKA might produce. In the 1 deg^2 field shown here, RMs can be detected for polarised fluxes as faint as 3 μJy, resulting in ≈500 RMs deg^{-2}, with an average separation between measurements of $2' - 3'$. Clearly any magnetised extended source in the foreground, whether directly emitting in the radio band or not, will be detected and probed by this "RM grid", allowing entirely new ways of studying magnetic fields in distant objects (see Gaensler et al. 2005).

We correspondingly envisage a wide-field SKA survey for RMs, in which $10\,000 - 20\,000$ deg^2 would be imaged in 1.4 GHz continuum emission and polarisation down to an RMS sensitivity of 0.1 μJy. For a 1-deg^2 field-of-view, this survey would require about 12 months of telescope time. The total intensity component of such a survey would also be an incredible resource for many other science projects, as demonstrated by the highly successful FIRST survey (Becker, White & Helfand 1995) (which unfortunately does not include polarisation).

Applying the $\log N - \log P$ function described above, we predict that this would yield $\sim (2-5) \times 10^7$ RMs over the sky, with a mean spacing between measurements of $\sim 90''$. In addition, virtually all the detectable radio pulsars in the Galaxy would be seen through their time-averaged emission, yielding an additional $\sim 20\,000$ pulsar RMs, concentrated in the Galactic plane (Cordes et al. 2004). In the following sections, we describe some of the scientific yields of the RM grid and of other polarisation measurements with the SKA (see Gaensler et al. 2004; Beck & Gaensler 2004; Feretti, Burigana & Enßlin 2004; Feretti & Johnston-Hollitt 2004, for further details and other possible projects).

5. The magnetic fields of galaxies and clusters

5.1. The Milky Way

Optical and radio polarisation studies have established that the Milky Way and many other nearby spiral galaxies all show well-organised, large-scale magnetic fields (Beck 2005). These coherent magnetic fields can be generated and preserved through the dynamo mechanism, in which small-scale turbulent fields are steadily amplified and ordered by differential rotation (Ruzmaikin, Sokolov & Shukurov 1988; Beck et al. 1996). However, dynamos are not yet well understood and still face theoretical difficulties (Kulsrud 1999).

Our own Milky Way is an excellent test-bed to address these issues, its large extent on the sky providing a huge ensemble of RMs which can be used to probe its three-dimensional magnetic field structure. Indeed, RMs for pulsars and for extragalactic sources have yielded the strength and orientation of the local regular magnetic field in the plane ($B \sim 2$ μG, directed approximately azimuthally), have allowed us to identify the overall geometry of the spiral magnetic pattern of our Galaxy, and have revealed the surprising presence of large-scale "magnetic reversals" (see Crutcher, Heiles & Troland 2003; Shukurov 2005; Beck 2006 for reviews). Unfortunately, the sparse sampling of RMs, and the paucity of pulsar polarisation measurements at distances larger than $\sim 6 - 8$ kpc, make it difficult to establish any consensus.

The SKA provides the opportunity to dramatically improve this situation. As mentioned above, RMs will be obtained for $\sim 20\,000$ pulsars, primarily concentrated in the Galactic plane. For many of these pulsars, good distance estimates will be obtained through either either astrometric parallaxes or H I absorption. The resulting dispersion measures and RMs can provide a comprehensive three-dimensional model of magnetic fields and ionised gas in the disk and spiral arms (e.g., Stepanov et al. 2002). On smaller scales, these data can also provide detailed measures of magnetic fields in individual sources such as supernova remnants and H II regions (Gaensler et al. 2001; Beck & Gaensler 2004), and can characterise the role of magnetic fields in interstellar turbulence (Lazio, Spangler & Cordes 1990; Minter & Spangler 1996). Alongside these measurements, the SKA will also produce spectacular images of diffuse polarised emission from individual sources and from the overall Galactic disk. By considering the appearance of these structures as a function of frequency, "Faraday tomography" can be performed, in

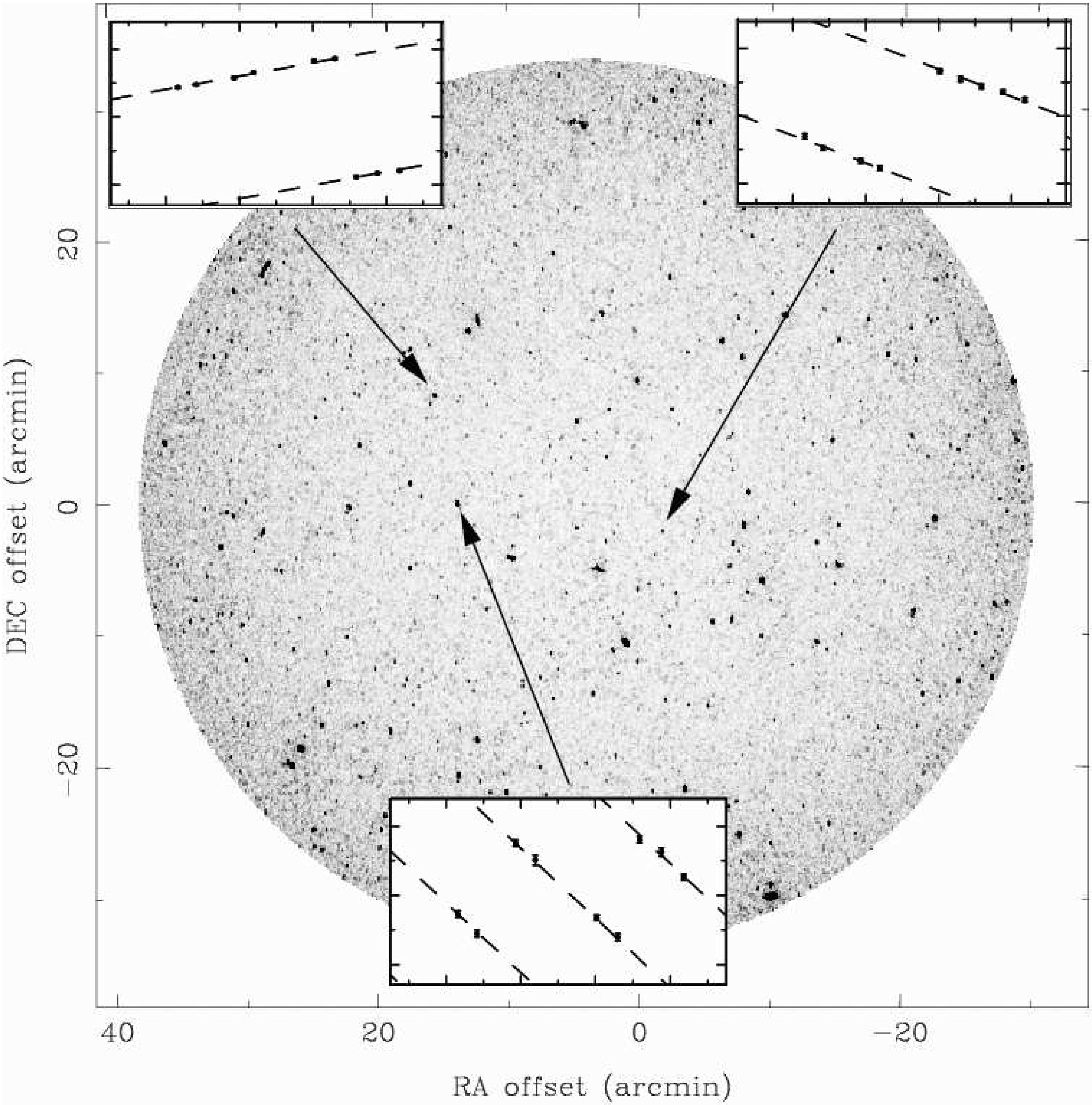

Fig. 2. A depiction of how the polarised sky at 1.4 GHz will appear to the SKA after a 5-min integration, based on the differential source count predictions of Beck & Gaensler (2004). The greyscale shows linearly polarised intensity over a 1-deg^2 field-of-view, with a correction for primary beam attenuation applied. The panels show polarisation position angle vs. wavelength squared for three compact sources in the field. A linear fit to each data-set is shown, the slope of which yields the RM. (This image is adapted from total intensity images of the Phoenix Deep Survey; Hopkins et al. 2003.)

which individual magneto-ionic structures along the line of sight can be isolated and studied (see Beck & Gaensler 2004).

Also of considerable interest is the magnetic field structure in the Galactic halo, and in the Galactic plane but at radii beyond the stellar disk where most pulsars are found. The dense background grid of extragalactic RMs can be used to map these regions, providing key information on the parity and overall geometry of the field.

5.2. Nearby galaxies and clusters

The same techniques as used for our Milky Way can be applied to more distant galaxies and clusters. Until recently, such efforts have been severely limited: Han, Beck & Berkhuijsen (1998) were able to find just 21 sources with RMs behind M 31, while Govoni et al. (2001) were able to identify only six sources with RMs for the cluster Abell 514. What the SKA will be able to provide is suggested by the recent RM survey of the Large Magellanic Cloud (LMC) by

Gaensler et al. (2005), in which about 100 background RMs were identified, as shown in Figure 3. This dense sampling allowed the first detailed studies of the LMC's magnetic field, revealing a coherent axisymmetric spiral field, on which large fluctuations on all scales are superimposed. This result provides clear evidence that field amplification in galaxies can be extremely rapid.

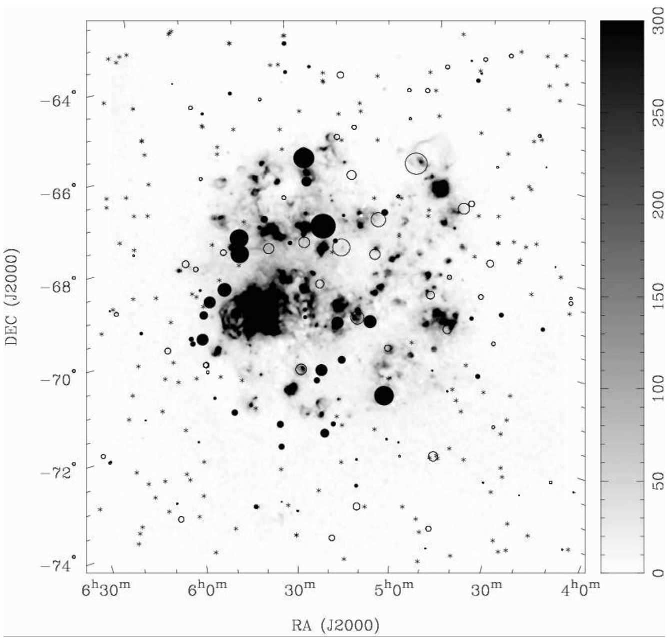

Fig. 3. Faraday rotation measures through the Large Magellanic Cloud (Gaensler et al. 2005). The image shows the distribution of extinction corrected emission measure toward the LMC in units of pc cm^{-6}, derived from the Hα survey of Gaustad et al. (2001). The symbols show the sign and magnitude of the RM at various positions (after subtraction of a mean baseline). Filled and open circles correspond to positive and negative RMs, respectively, while asterisks indicate RMs which are consistent with zero within their errors. The diameter of each circle is proportional to the magnitude of the RM, the largest positive and negative RMs being $+247 \pm 13$ rad m^{-2} and -215 ± 32 rad m^{-2}, respectively.

With the SKA, this same approach can be extended to many other systems. For the nearest galaxies, deep SKA observations will provide $> 10^5$ background RMs, and thus will yield fantastically detailed maps of the magnetic structure. Several hundred more galaxies will have ~ 50 RMs behind them. These data will provide maps of galactic magnetic fields to large galactic radii for a wide range of inclinations, galaxy types and environments. These statistics will provide stunning new constraints for dynamo and other theories (see Beck, these proceedings).

In galaxy clusters, magnetic fields regulate heat conduction, and regulate cluster formation and evolution. There are a variety of ways of measuring the field strength (Carilli & Taylor 2002), but measurements of the field geometry can come only from RMs of background or embedded sources (for which there are typically < 5 sources per cluster), and from measurements of the polarisation position angle of diffuse emission from the cluster itself (which is usually of very low surface brightness). With the SKA, the RM grid can provide ~ 1000 background RMs behind a typical cluster, while continuum mapping with the core of the array will detect extended polarisation from both relic and halo components (e.g., de Bruyn & Brentjens 2005; Govoni et al. 2005). One can apply the technique of "RM synthesis" to these data, in which a cube of polarisation vs. wavelength squared is Fourier transformed to yield the signal as a function of Faraday depth (Brentjens & de Bruyn 2005). Through this approach, a three-dimensional dissection of the cluster's magnetic structure can be derived. Furthermore, detailed comparisons between RMs and X-ray emission in clusters will be possible, allowing us to relate the efficiency of thermal conduction to the magnetic properties of different regions, and to directly study the interplay between magnetic fields and hot gas.

For both clusters and individual galaxies, further information can be obtained when the polarised sources against which RMs are being derived are extended. Over limited regions, this then provides a map of RM in the foreground source at the full resolution of the observations, from which the magnetic field power spectrum in the interstellar and intercluster medium can be derived (e.g., Vogt & Enßlin 2003).

5.3. Polarisation silhouettes

At intermediate redshifts, galaxies and clusters become too small to be usefully probed by the RM grid. However, one can study magnetic fields in these sources when they lie in front of distant, extended, polarised sources. The foreground Faraday rotation then produces a "polarisation silhouette". A good example of this is NGC 1310, a spiral galaxy which has depolarised a small part of the radio lobe of Fornax A, as shown in Figure 4 (Fomalont et al. 1989). The RM and fractional polarisation as a function of both position and frequency toward NGC 1310 can then be used to derive both the coherent and ordered components of this galaxy's magnetic field (Schulman & Fomalont 1992).

While NGC 1310 is reasonably nearby, this same technique can readily be applied to more distant sources. Several examples of such silhouettes have already been identified in the literature (e.g., Kronberg, Perry & Zukowski 1992; Johnson, Leahy & Garrington 1995). With the SKA, observations of high resolution and sensitivity can identify many such sources, at a range of redshifts. These data then become a powerful probe of the evolution of galactic magnetism over the last few billion years.

5.4. Lyman-α absorbers at $z \sim 1 - 3$

Most quasars have many foreground clouds along the line-of-sight, as evidenced by the Ly-α forest seen in their optical spectra. If both the RM and the redshift of a quasar is known, then the correlation of RM vs. redshift, averaged over a large sample of quasars, should directly trace the evolution of magnetic fields in galaxies and proto-galaxies out to large

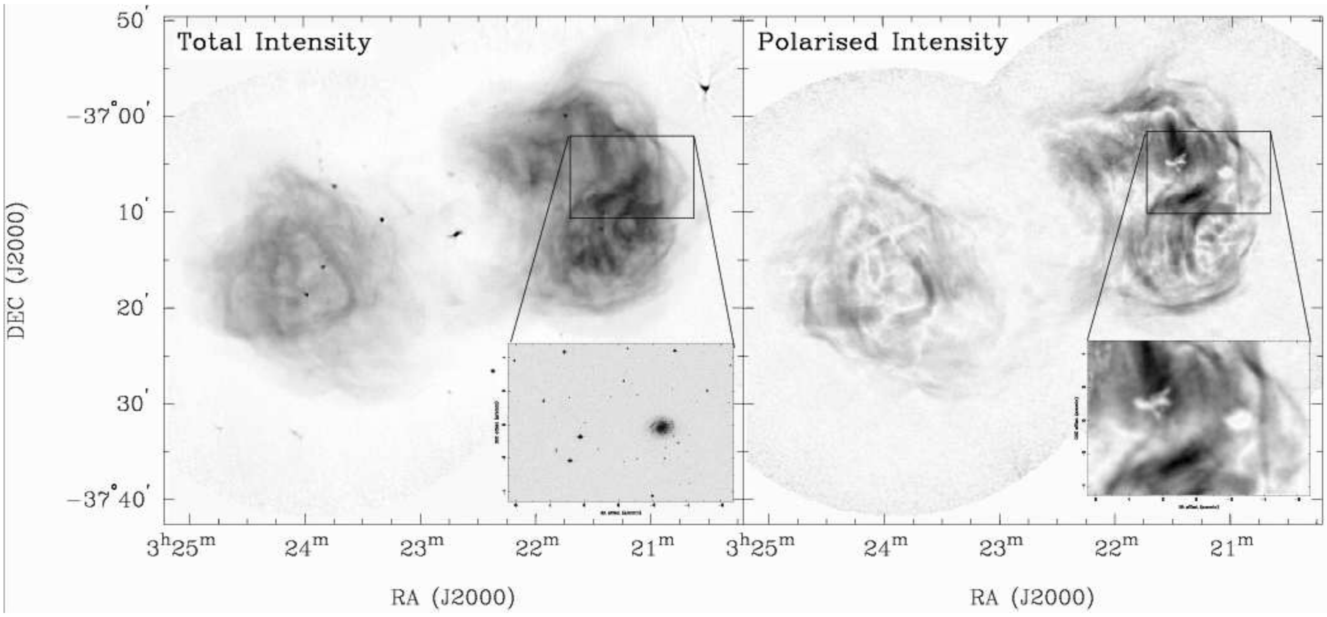

Fig. 4. Comparison of total intensity (left) and polarised (right) radio emission from the giant radio galaxy Fornax A (Fomalont et al. 1989). The insets show a close-up of the western lobe. The left inset shows optical emission from the Digitized Sky Survey, in which NGC 1310 can clearly be seen. The right inset shows linear polarisation, in which NGC 1310 clearly depolarises the lobe behind it.

distances (e.g., Welter, Perry & Kronberg 1984). This experiment has been attempted several times with existing data sets, but the small sample size, combined with the difficulty of accounting for the foreground RM contribution from the Milky Way, has meant that these data provide only marginal (if any) evidence for any evolution of RM with redshift (Perry, Watson & Kronberg 1993; Oren & Wolfe 1995).

In the future, we expect dramatic improvements. First, the SKA should be able to identify RMs toward many millions of quasars, a much larger sample than is available now. Second, it should be straightforward to accurately remove the spatially varying foreground contribution to the RM, because of the very dense sampling of other RM measurements projected near each quasar. Finally, by combining these data with the wide-field spectroscopic surveys planned with WFMOS, and with all-sky multi-band photometry with LSST and SkyMapper, redshifts (and for spectroscopic studies, information on the number and depth of absorbing systems) can be obtained for a large fraction of the quasars with RMs. The result will be a detailed probe of how magnetic fields evolve in galaxies and their progenitors out to moderate redshifts.

6. The magnetised intergalactic medium

It is quite likely that the overall IGM is magnetised, although direct detection of these fields has so far been difficult, with upper limits in the range $|B_{\rm IGM}| \lesssim 10^{-8} - 10^{-9}$ G (Kronberg 1994; Blasi, Burles & Olinto 1999; Jedamzik, Katalinić & Olinto 2000). This magnetic field may represent the seed field for galaxies and clusters, and may play an important role in reionisation and in the formation of large-scale structure (Wasserman 1978; Sethi & Subramanian 2005). The origin of magnetism in the IGM is unclear: it may be a primordial field formed in the very early Universe, it may be injected into the IGM by stars or active galaxies, or it may be generated in the shocks and turbulence produced in clusters and supernova remnants (Furlanetto & Loeb 2001; Kronberg, these proceedings; Hanayama et al., these proceedings; Fujita & Kato, these proceedings).

In principle, the magnetic field of the IGM can be identified through RM measurements of distant sources. Specifically, if there are large-scale magnetic fields on a particular scale, then given sufficient statistics, the angular correlation function of RMs for a given redshift bin should show a signal (Kolatt 1998). For a range of scales and a range of redshifts, the magnetic power spectrum of the IGM can then be determined (Blasi et al. 1999).

There are various difficulties with this experiment, including the need to accurately remove the Galactic foreground RM (as discussed in Sect. 5.4), and the small sample size of RMs currently available. Furthermore, the signal is easiest observed at higher redshifts, where co-moving magnetic field strengths and electron densities are presumed to be higher. For an RM sample dominated by sources with redshifts $z \lesssim 0.5 - 1$, identifying this signal is difficult.

We thus envisage observations of very deep polarisation fields with the SKA, in which a large number of RMs at a variety of redshifts would be identified (the total intensity component of these data would have many other applications; e.g., Jackson 2004). Accompanying optical and infrared surveys could provide identifications the polarised sources, and could determine their redshifts. With such a data-set in hand, we can expect to directly detect the IGM field, and determine its strength, structure, and characteristic length scales.

Several authors have modeled the magnetised intergalactic shocks which trace the large-scale structure of the Uni-

verse, and which should themselves emit in synchrotron emission (Keshet, Waxman & Loeb 2004a; Brüggen et al. 2005). Some of this structure has been hinted at in observations (Bagchi et al. 2002; Kronberg, these proceedings). The SKA will have the capability to carry out very sensitive, wide field surveys of emission at low frequencies. If foregrounds can be accurately removed, we may thus be able to map these shocks in total intensity, providing a direct estimate of the strength and degree of ordering of magnetic fields in these structures (Keshet, Waxman & Loeb 2004b). If these shocks can also be detected in linear polarisation, the three-dimensional geometry of the magnetic field (and presumably of the underlying structure) can be determined. Brentjens & de Bruyn (2005) have demonstrated the utility of RM synthesis at low frequencies, where there is good sensitivity to very small changes in RM. Application of this technique to polarised large-scale structure may be feasible.

7. Magnetic fields at high redshift

As discussed by Zweibel (these proceedings) and by Kronberg (these proceedings), there is good evidence for the existence of microgauss strength magnetic fields at redshifts $z \sim 1 - 2$. If these measurements can be extended to redshifts $z > 5$, the strength of the field at these early epochs may provide constraints on how the field was created and then amplified.

The SKA and its pathfinders are expected to identify many polarised radio sources at high redshift, for which RMs can be measured — examples include gamma-ray burst afterglows (e.g., GRB 050904 at $z = 6.29$; Kawai et al. 2005) and distant radio galaxies (e.g., SDSS J1148+5251 at $z = 6.43$; Carilli et al. 2004b). Since the RMs toward these sources represent an integral along the entire sight-line, foreground components need to be removed to isolate the RM contribution at high z. This can be achieved by deep radio and optical observations of these fields, which will identify many polarised sources in close angular proximity to the target source, but at lower redshifts.

At much higher redshifts, RMs may be detectable against the polarised signal from the cosmic microwave background (e.g., Kosowsky et al. 2005). However, this experiment could be challenging, because of the small position angle changes expected at high frequencies ($\nu > 20$ GHz).

8. Polarisation pathfinders for the SKA

While the full SKA is perhaps a decade or more in the future, a number of polarisation pathfinder experiments are now being built, which will begin to characterise the polarised sky, and which can consequently be used to explore some of the topics discussed above. These efforts include:

– The Galactic Arecibo L-Band Feed Array Continuum Transit Survey (GALFACTS),[2] a 1.4-GHz survey to begin later in 2006 to map the entire polarised sky visible to Arecibo;
– The Low Frequency Array (LOFAR),[3] currently under construction in the Netherlands and Germany, which will study polarisation over the whole northern sky at very low frequencies ($\nu = 30 - -80, 110 - -240$ MHz);
– The Allen Telescope Array (ATA),[4] currently being constructed in northern California, which will have a wide field of view (5 deg^2 at 1.4 GHz) and can carry out very large continuum surveys;
– The Square Kilometre Array Molonglo Prototype (SKAMP), a refurbishment of the Molonglo Observatory Synthesis Telescope in south-eastern Australia, which will provide 18 000 m^2 of collecting area for studying diffuse polarisation at frequencies $\sim$ 1 GHz over wide fields;
– The Low Frequency Demonstrator component of the Mileura Wide Field Array (MWA),[5] an interferometer to be built in Western Australia, which will study polarised emission over wide fields in the frequency range 80–300 MHz;
– The extended New Technology Demonstrator (xNTD)[6] and the Karoo Array Telescope (KAT),[7] arrays to be built in South Africa and Western Australia, respectively, both of which will be very wide-field (30–40 deg^2 at 1.4 GHz) survey instruments, and which can study polarisation at a range of spatial scales in the approximate frequency range 800–1700 MHz.

All these facilities are under construction, and should be operational in the next 2–5 years. These telescopes will provide ~100 000 RMs and measurements of diffuse polarisation all over the sky, allowing many new studies of RM synthesis, polarisation silhouettes, and other experiments discussed above.

9. Conclusions

"Cosmic Magnetism" has been named as one of five key science projects for the SKA. This telescope will open an entirely new regime for probing magnetic fields at all redshifts, and will provide unique radio data that can complement other information delivered on magnetic fields by Auger, HESS, *Planck* and *GLAST*. The considerable new parameter space opened up by the SKA implies that in addition to the experiments that we can conceive today, the SKA will almost certainly discover entirely new and unexpected magnetic phenomena.

In the years leading up to the construction and commissioning of the SKA, we encourage theorists to include RM and polarisation predictions in their calculations, and observers to start thinking about other magnetic experiments that the SKA could carry out. In the meantime, the magnetic field community can look forward to the SKA pathfinders delivering a great deal of new data on the polarised sky.

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2 http://www.ras.ucalgary.ca/GALFACTS

3 http://www.lofar.org

4 http://astron.berkeley.edu/ral/ata

5 http://web.haystack.mit.edu/arrays/MWA/LFD

6 http://www.atnf.csiro.au/projects/ska/xntd.html

7 http://www.ska.ac.za/kat/

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